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Significance of Delta Ferrite Content to Fatigue Crack Growth Resistance of Austenitic Stainless Steel Weld Deposits

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The potential contribution of delta ferrite content to pre- and postirradiation fatigue crack growth resistance was explored using a series of shielded metal arc weldments (Type 304 base, Type 308 Filler). Delta ferrite contents ranged from ferrite number 5.2 to 19.0. Fatigue crack growth rates were determined at 260, 427, and 649°C using single-edge-notch (SEN) specimens cycled in air under zero-tension-zero loading. Crack growth rate per cycle, da/dN, was related to stress intensity factor range, ΔK.

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20. ABSTRACT – (continued)

Results for the preirradiation (as-welded) condition show that delta ferrite content and temperature variations in the ranges studied do not exert a significant influence on the fatigue resistance of Type 308 welds under continuous cycling at 10 cpm. Addition of a 0.5 tension hold-period to the load pattern did not change 427°C fatigue resistance. However, results for a 649°C postirradiation condition did reveal an apparent relationship between fatigue resistance and delta ferrite content and a potential for increased fatigue crack growth rates by irradiation.

CONTENTS

SIGNIFICANCE OF DELTA FERRITE CONTENT TO FATIGUE CRACK GROWTH RESISTANCE OF AUSTENITIC STAINLESS STEEL WELD DEPOSITS

INTRODUCTION

The influence of delta ferrite content on the mechanical properties of austenitic stainless steel welds is being evaluated by the Naval Research Laboratory (NRL) for the Army Engineer Power Group and the Energy Research and Development Administration (ERDA). The investigations, aimed at current and projected weld applications in nuclear reactor structures, encompass both preirradiation and postirradiation conditions and focus on fatigue and notch toughness properties. The investigations were prompted not only by the extensive use of welded stainless steel in conventional and advanced (planned) reactor systems but also by prior observations of large variations in fatigue and fracture properties among typical welds [1,2]. Several metallurgical factors may be responsible for the noted observations. The NRL studies are attempting to isolate the primary variables contributing to such variability and have, as a long-term objective, the development of guidelines for improved welds for nuclear service.

This report describes initial exploratory tests of fatigue crack growth resistance changes with one metallurgical variable, delta ferrite content, over a broad range of service temperatures. An initial study of the delta ferrite contribution to postirradiation fatigue behavior is also described. Reports documenting results of a companion study on preirradiation notch ductility characteristics versus delta ferrite content have been issued ~~[3,4]~~.

MATERIALS

The range of delta ferrite content of most interest to reactor applications is approximately from 5 to 15 percent. A series of four 6.4 cm (2-1/2 in.) thick shielded metal arc weldments (Type 304 base plate, Type 308 filler) encompassing this range were obtained for the investigations from the Arcos Corporation by contract. The electrode composition and coatings used were those developed by Arcos for a prior Metal Properties Council (MPC) project. A reference plate from NRL stock served as base material.

Chemical compositions of the weld deposits are listed in Table 1. Welding parameters and conditions are documented elsewhere [3]. Each weld was a full-thickness weld (1.9 cm (3/4 in.) minimum weld width), the root regions were arc-air back gouged and ground to all weld metal after layer seven. Welding was accomplished under full mechanical restraint, however, opposite faces were welded alternately in a sequence designed to minimize unbalanced stresses. Delta ferrite contents of the individual welds in ferrite number, as determined by Magne-Gage*, were 5.2, 10.4, 15.7, and 19.0, respectively.

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*A magnetism test device

SPECIMEN DESIGN AND EVALUATION

Single-edge-notch (SEN) cantilever fatigue specimens were used wherein the plane of the fatigue crack was oriented parallel to the welding direction and perpendicular to the weldment surface. The features and dimensions of the SEN specimen are shown in Fig. 1. All weld specimens were composite specimens made by joining (electron beam or metal inert-gas welding) end tabs to a center test section 5.5 X 6.4 X 1.3 cm in size. Comparisons of welded vs nonwelded specimens of similar materials (AISI Type 316 plate and welds) have indicated that test results from each are comparable [5].

All tests were conducted in air using a zero-tension-zero loading cycle. Specimen temperatures were provided by induction heating and were monitored continuously during testing by thermocouples. Tests normally were interrupted during nonworking hours and were resumed only after the specimens had again reached temperature. No noticeable effect of this procedure was seen in the data.

Crack length measurements were accomplished by means of a traveling microscope at a magnification of X35 or by means of a high-resolution, closed-circuit television system. The television system was used for those tests conducted remotely in the NRL hot-cell facility. Rates of crack growth were established from plots of crack length vs number of cycles using the ASTM-recommended incremental polynomial method. The method basically involved computer fitting, by least squares criteria, seven consecutive data points (N_{i-3} to N_{i+3}) to a second order polynomial. The polynomial in turn is differentiated to yield da/dN to the N_i^{th} point.

The SEN specimen crack growth rates (da/dN) were related to stress-intensity factor range (ΔK) using the expression for K for pure bending developed by Gross and Srawley [6]:

Table 1 — Chemical Compositions of AISI Type 308 Shielded Metal Arc Weld Series With Variable Delta Ferrite Content

NRL Weld Code	Delta Ferrite Content[a]	Chemical Composition (wt-%)[b]								
		C	Mn	Si	P	S	Cr	Ni	Mo	N
V41 (178 AA)	5.2	0.056	1.88	0.32	0.024	0.011	19.71	10.35	0.05	0.068
V42 (179 A)	10.4	0.060	1.54	0.31	0.029	0.009	19.90	9.25	0.05	0.074
V43 (180 A)	15.7	0.060	1.65	0.32	0.029	0.011	20.89	9.11	0.06	0.079
V44 (181 KA)	19.0	0.060	1.38	0.43	0.028	0.010	21.08	8.93	0.08	0.084

[a] Weld deposit ferrite number (avg); Magne-Gage determination.
[b] Composition based on standard WRC weld test pad (courtesy Arcos Corporation), core wire for all electrodes from same steel melt

$$K = \frac{6PL}{(BB_n)^{1/2} \cdot W^{3/2}} \cdot Y, \qquad (1)$$

where $Y = 1.99\,(a/W)^{1/2} - 2.47\,(a/W)^{3/2} + 12.97\,(a/W)^{5/2} - 23.17\,(a/W)^{7/2} + 24.80\,(a/W)^{9/2}$, and where P is the cyclic load, L is the distance from the crack plane to the point of load application, a is the total length of notch and crack, W is the specimen width, B is the specimen thickness, and B_n is the net thickness between the specimen side grooves. A correction for plasticity at the crack tip was not made. Tests of the SEN specimens normally were terminated when the total flaw length, a, reached about 3.8 cm (1.5 in.).

EXPERIMENTAL TEST MATRIX

The test matrix employed for the present study is outlined in Table 2. The matrix permits a determination of temperature effects as well as delta ferrite content effects on weld properties. The test temperature of 260°C corresponds to the operating temperature of the Army MH-1A reactor vessel; the 427°C and 649°C test temperatures were chosen to generally bracket the operating-temperature range projected for many fast breeder reactor components. As noted, the matrix called for a fatigue-cycling rate of 10 cpm (sawtooth test mode). One test (V44-7) was made at a cycling rate of 2 cpm with a 0.5 m tension hold time. Loading and unloading rates for the hold-time test were the same as those for the continuous-cycling tests.

Not shown in Table 2, a postirradiation comparison for welds V42 and V44 was also developed. The specimens were irradiated at 649°C in the EBR-II reactor (subassembly X-266) to $\sim 0.9 \times 10^{22}$ n/cm² >0.[illegible] MeV and were subsequently tested at 649°C at 10 cpm. A controlled-temperature, heat-pipe irradiation assembly was used. The period of irradiation was 3110 hours; total time in reactor was about 6000 hours. Specimen temperatures during reactor downtimes were approximately 371°C.

Table 2 — Experimental Test Matrix[a]
(Unirradiated Condition)

Weld Code	Ferrite Number	Test Temperature		
		260C(500F)	427C(800F)	649C(1200F)
V41	5.2	3[b]	6,8	7
V42	10.4	9	6	3
V43	15.7	3	5	6
V44	19.0	9	6,7[c]	3

[a]Zero-tension-zero loading, 10 cpm continuous cycling mode except as noted
[b]Specimen ID number (typical)
[c]Zero-tension-zero loading, 2 cpm cycling with 0.5 min tension hold

RESULTS AND DISCUSSION

Experimental results pertaining to the preirradiation condition are presented in Figs. 2 through 8. Initial findings for the 649°C postirradiation condition for welds V42 and V44 are shown in Fig. 9. Two general observations can be made immediately. First, overall differences among all preirradiation condition results are relatively small. Secondly, the data appear to conform to a power-law relationship of the form: $da/dN = C(\Delta K)^m$.

Effect of Delta Ferrite Content

Figures 2, 3, and 4, showing the performance of the welds at given test temperatures, indicate essentially no effect of delta-ferrite content on fatigue crack growth resistance for the range investigated. That is, no discernible trend of behavior with increasing ferrite content is found. Rather, the data appear to fall within a single data-scatter band at each temperature. Figure 5 gives some indication of the extent of data scatter possible for an individual weld. The specimens in this example represent two test locations through the weld thickness.*

Effect of Test Temperature

Figures 6 and 7 summarize individual results for welds V42 and V44, respectively, for the three test temperatures. These particular comparisons are indicative of the extremes in temperature sensitivity observed among the four welds. Comparable fatigue crack growth resistance is clearly demonstrated for 427°C versus 649°C temperature conditions; however, a trend toward a slightly-lower fatigue crack growth rate was shown consistently in the case of 260°C testing. On balance, the data reveal very low weld sensitivity to those temperature conditions investigated. With reference to the 649°C test results, sigma phase formation is not evident from the data trend characteristics. The duration of tests in this case was in excess of 40 hours. Sigma phase development and its potential contribution to fatigue crack growth resistance will be explored further in conjunction with experimental evaluation of long-term thermal-conditioning effects versus reactor irradiation effects.

Effect of Tension Hold Time

Figure 8 compares trends in the 427°C fatigue resistance of weld V44 under continuous cycling versus cycling with a 0.5-minute tension hold-time. The data describe similar fatigue crack growth rates for most of the ΔK range. This observation is supported by one made in an earlier study for Type 316 stainless steel welds [1] which compared the effects of 10-cpm cycling versus 1-cpm cycling with a 54-second hold-time. In both cases, continuous cycling produced growth rates similar to those from cycling with a tension-hold up to ΔK values of about 50 $MPa\sqrt{m}$ (45 $ksi\sqrt{in.}$). Above this ΔK value, somewhat greater growth rates were noted for the continuous-cycling mode. In contrast to these observations, Shahinian [7] found an increase in growth rate at 427°C with the inclusion of a 0.1-minute hold at peak load using a similar Type 308 weld. His data trend curves are

*The data for specimen V41-6 should be taken with some reservation in that the specimen was briefly over heated to 704°C prior to initial cycling.

shown in Fig. 8 (dashed lines). Enhanced recovery of residual stresses during the hold period was advanced as a possible explanation for the hold-time effect.

The inconsistency between Shahinian's observation and those of the present study may be due to residual element content differences between the respective welds. In the former case, the weld represented a controlled residual element (CRE) composition modification of Type 308 which was specially developed for certain fast breeder reactor applications. It is noted that the CRE and non-CRE welds show a significant (2:1) difference in growth rate with tension-hold cycling and low ΔK values. On the other hand, the welds show comparable fatigue resistance under continuous cycling over the entire ΔK range investigated. Further investigation of hold-time and composition variables clearly is warranted. For Type 304 stainless steel plate, fatigue crack growth at 427°C does not appear to be changed if a tension hold is applied [8].

Effect of Neutron Irradiation

Figure 9 presents findings for two welds irradiated and tested at 649°C. In this exploratory comparison, an apparent relationship between delta ferrite content and radiation-induced change in fatigue crack growth resistance is clearly evident. That is, weld V44, but not weld V42, shows a large change in behavior over the preirradiation condition at ΔK values greater than ~ 22 MPa$\sqrt{m}$ (20 ksi$\sqrt{in.}$). Secondly, the radiation-induced change is in the direction of higher growth rate. Whether or not the observed difference is due to thermal effects during the 649°C reactor exposure or radiation effects (or a combination thereof) will be investigated along with associated mechanisms by the continuing program.

In an earlier exploration of radiation effects, a submerged-arc Type 316 weld deposit (ferrite number 11.1) irradiated in a water-cooled reactor and tested at 260°C showed reduced crack growth rates after irradiation. The neutron fluence ($\sim 9 \times 10^{19}$ n/cm^2 >0.1 MeV) as well as the exposure temperature was much lower than those of the present study. The observation here may not be inconsistent in that a change in the radiation effects mechanism between the two exposure temperatures is a distinct possibility. At 260°C, radiation effects are generally associated with the production of small defect clusters. At 649°C, on the other hand, radiation effects are associated with the formation of coarse dislocation networks (and possibly voids). Also, at the higher temperature, radiation-induced precipitate formation is considered a possibility.

FUTURE EFFORTS

The absence of pronounced differences in preirradiation fatigue crack growth resistance due to delta ferrite content or test temperature is consistent with reported findings on Charpy-V notch ductility and strength determinations for the welds [3]. With the exception of a determination of long-term thermal-conditioning effects to the welds, studies of the preirradiation condition are therefore considered complete. The main thrust of the continuing investigations will be toward assessments of the contribution of delta ferrite content to postirradiation trends. Toward this end, EBR-II experiments are underway that involve both 427 and 649°C exposures and test temperatures. Findings of these studies should become available in 1979.

SUMMARY AND CONCLUSIONS

A series of four AISI Type 308 weld deposits (shielded metal-arc process) representing a range of delta ferrite contents from ferrite number (FN) 5.2 to 19.0 have been evaluated for fatigue crack growth resistance at three elevated temperatures. The study focused on weld comparisons in the unirradiated condition; however, an exploratory assessment of the significance of delta ferrite content to fatigue resistance after neutron irradiation was also made.

Primary observations and conclusions drawn for the unirradiated test condition were:

1. Delta ferrite content variations within the range investigated do not result in a major difference in fatigue crack growth behavior for Type 308 weld deposits at either 260, 427, or 649°C for the case of fatigue cycling without a tension-hold period.

2. Fatigue cycling at 427°C with a 0.5-minute tension-hold period produces essentially the same fatigue crack growth trend as fatigue cycling at 10 cpm without a tension-hold period.

3. The fatigue crack growth resistance of Type 308 weld deposits is not appreciably governed by temperature within the range investigated. Fatigue crack growth trends at 427 and 649°C were found to be essentially coincident; at 260°C, a tendency toward lower fatigue crack growth rates was discerned in the data.

4. The controlled residual element (CRE) composition modification of Type 308 developed for certain fast breeder reactor applications may be less resistant to fatigue crack growth than the non-CRE composition at 427°C under certain fatigue cycling modes, i.e., cycling with a tension-hold period.

Primary observations for the postirradiation condition based on results for two welds tested at 649°C after $\sim 0.9 \times 10^{22}$ n/cm^2 >0.1 MeV at 649°C were:

1. An apparent relationship exists between 649°C postirradiation fatigue crack growth resistance and delta ferrite content.

2. Reduced 649°C fatigue crack growth resistance is produced by 649°C irradiation of welds with FN 19.0 but not welds with FN 10.4.

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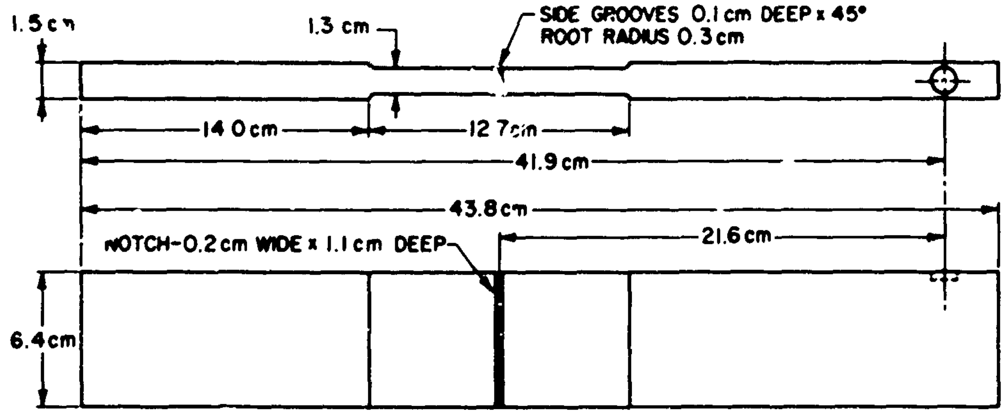

Fig. 1 — Design of single-edge-notch (SEN) cantilever fatigue test specimen

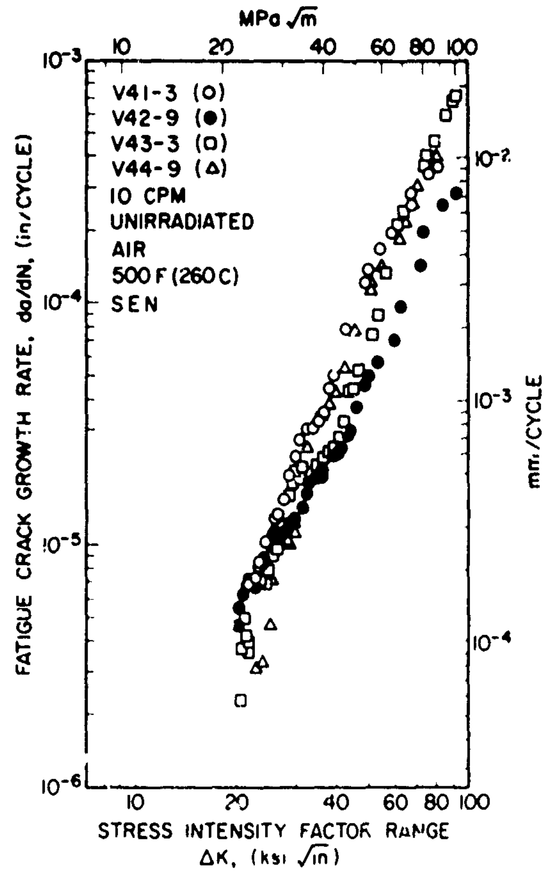

Fig. 2 — Fatigue crack growth rates of the weld series in the preirradiation (as-welded) condition at 260°C

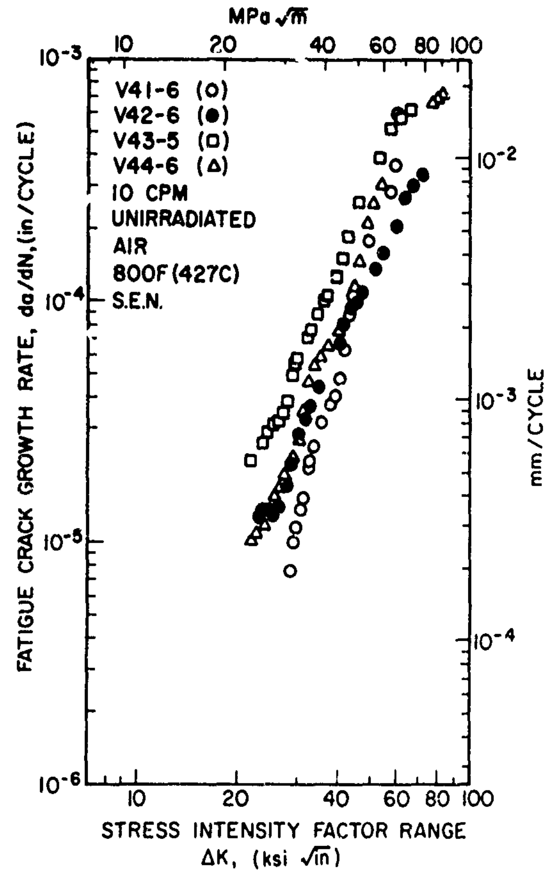

Fig. 3 — Fatigue crack growth rates of the weld series in the preirradiation condition at 427°C

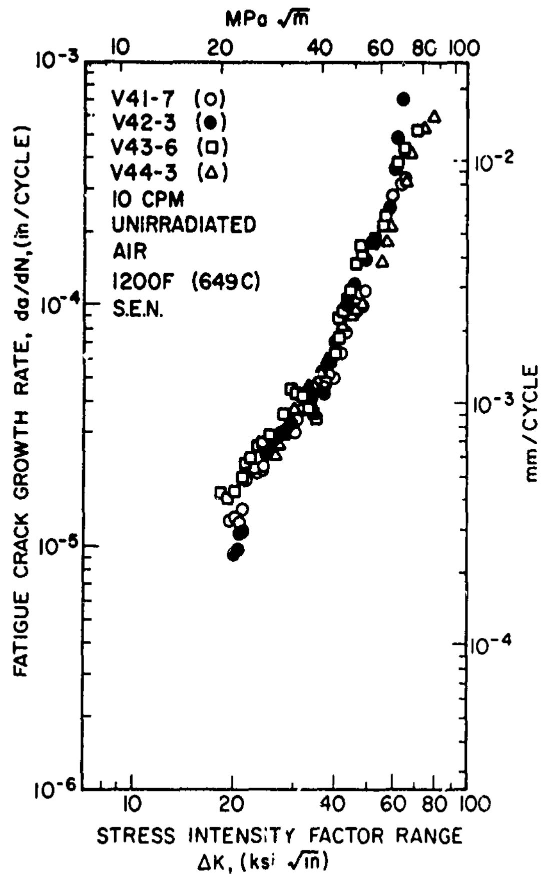

Fig. 4 — Fatigue crack growth rates of the weld series in the preirradiation condition at 649°C

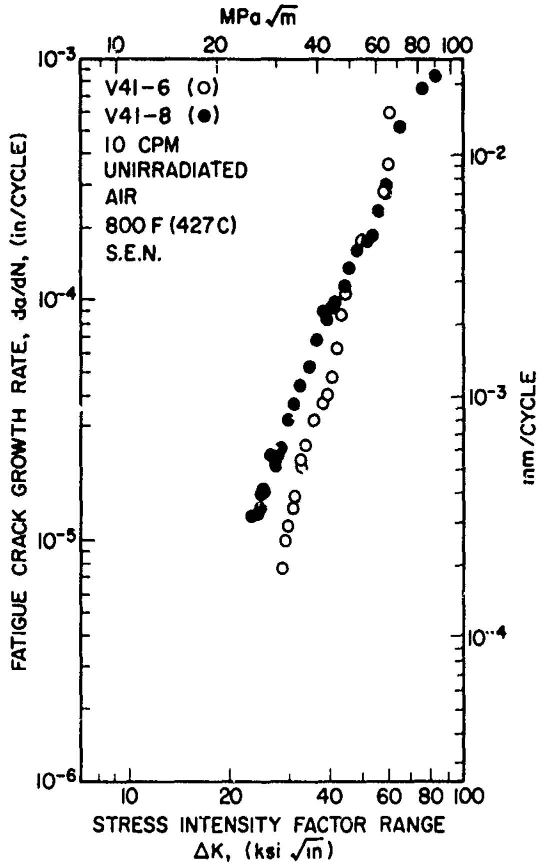

Fig. 5 — Variation in fatigue crack growth resistance of weld V41 observed between duplicate 427°C tests

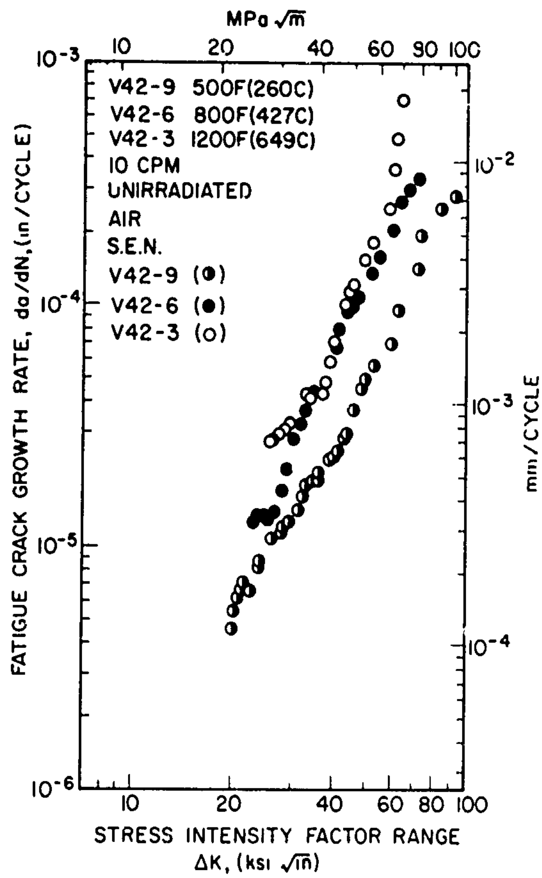

Fig. 6 — Effect of temperature on fatigue crack growth resistance of weld V42

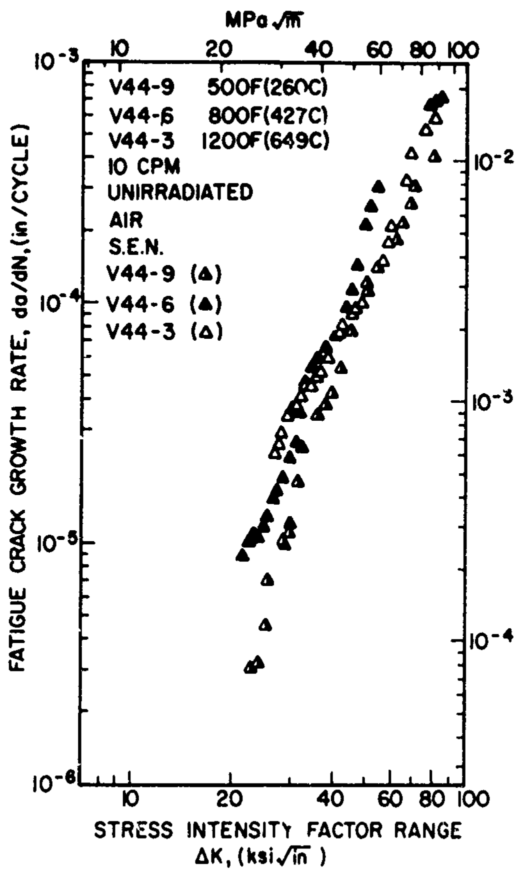

Fig. 7 — Effect of temperature on fatigue crack growth resistance of weld V44

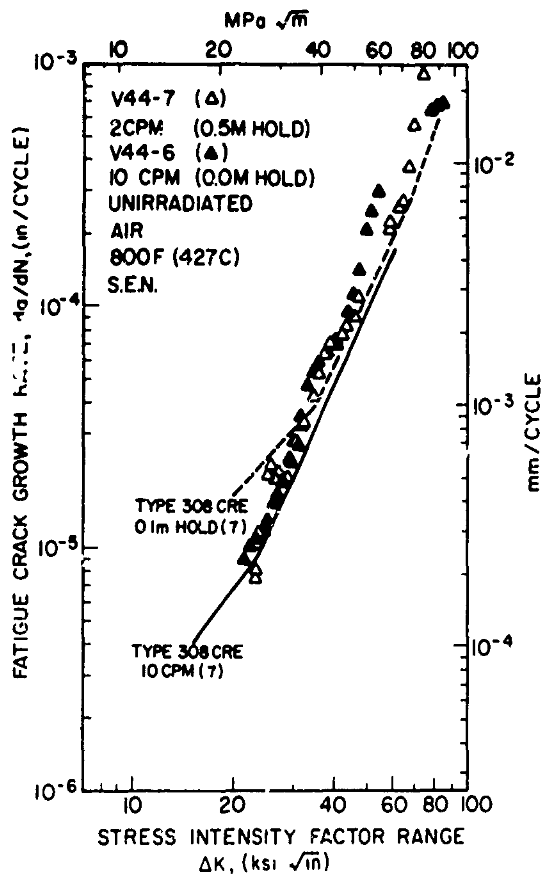

Fig. 8 — Variation in fatigue crack growth resistance of weld V42 with and without a 0.5-minute tension hold-time added to the basic load pattern (Trends observed by Shahinian [7] for a controlled residual element composition modification of Type 308 are also shown.)

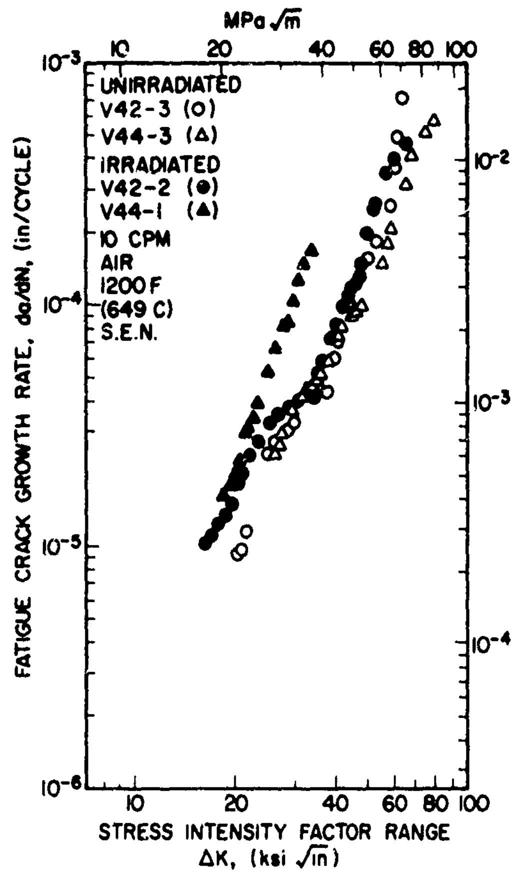

Fig. 9 — Effect of 649°C neutron irradiation on the 649°C fatigue crack growth resistance of weld V42 (FN 10.2) and weld V44 (FN 19.0)